

Geometry Optimization of Five-Phase Permanent Magnet Synchronous Motors using Bees Algorithm

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Abstract: Among all types of electrical motors, Permanent Magnet Synchronous Motors (PMSMs) are reliable and efficient motors in industrial applications. Because of their superiority over other kinds of motors, they are replacing conventional electric motors. On the other hand, high-phase PMSMs are good candidates to be used in certain industrial and military projects such as electric vehicles, spacecrafts, naval systems and etc. In these cases, the motor has to be designed with minimum volume and high torque and efficiency. Design optimization can improve their features noticeably, thus reduce volume and enhance performance of motors. In this paper, a new method for optimum design of a five-phase surface-mounted permanent magnet synchronous motor is presented to achieve minimum Permanent Magnets (PMs) volume with an increased torque and efficiency. Design optimization is performed in search for optimum dimensions of the motor and its permanent magnets using Bees Algorithm (BA). The design optimization results in a motor with great improvement regarding the original motor which is compared with two well-known evolutionary algorithms i.e. GA and PSO. Finally, finite element method simulation is utilized to validate the accuracy of the design.

Keywords: Bees Algorithm (BA), Design Optimization, Finite Element Method (FEM), Permanent Magnets (PMs).

1 Introduction

Permanent Magnet Synchronous Motors (PMSMs) are one of the most proper and efficient motors in electricity industry. Development of manufacturing technologies provides a situation where PMSMs can be economic with respect to conventional machines like induction and other traditional motors. Besides, these motors are good candidate for applications such as naval and space systems, electric vehicles and etc. Replacing excitation winding of rotor with Permanent Magnets (PMs) makes these motors more efficient than their excited counterparts; hence they are used in applications with high efficiency. The most important advantages of such motors are: high efficiency and power density, low loss, low maintenance cost, easy construction and etc [1-6].

One of the most interesting applications of PMSMs is to use as engine propeller of unmanned vehicles. Due to low space and limited capacity of batteries, having maximum efficiency and minimum volume is of great concern in such systems. Hence, design optimization

can enhance operational characteristics of motors. On the other side, these applications demand high reliability. In electrical motors, reliability increases with increase in number of phases in motor. High-phase motors are developed to obtain the highest possible reliability. In fact, in high-phase motors when one or two phases of motor are out of service due to failure, motor can continue to operate and overcome the fault [7-10].

There is great number of researches in literature dealing with optimum design of PMSMs. For example, in [11] authors presented a finite-Element based multi-objective optimization applied to interior PMSM. The optimization procedure is performed to design two IPMSM motors. Objective functions of this paper are reducing in weight and maximizing output power with wide constant-power region operation. In [12], design optimization of a permanent magnet synchronous motor was presented by artificial bee colony algorithm. Aim of the paper was to optimize the surface-mounted PMSM with geometrical variables and it the superiority of the proposed method was confirmed by comparison with Genetic Algorithm. In other research geometry optimization of PMSMs comparing full and fractional pitch winding configurations for aerospace actuation applications is presented [13] where the proposed

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algorithm combines technical and physical advantages of the two mentioned configuration. Ref. [14] has presented an automated multi-objective design optimization for permanent magnet AC Machines with the help of finite element analysis and differential evolution in which a wide range of PM machines can be optimally designed. In [15] optimum design criteria for maximum torque and efficiency of a line-start PMSM is presented using response surface methodology and finite element method. Jannot et al. [16] have presented a multi-physic modeling of a high speed PMSM which is carried out with Genetic algorithm optimization where objective functions are efficiency and weight of motor. A design optimization of PMSM for high torque capability and low magnet volume has been presented in Ref. [17] where objective function is a combination of torque and magnet volume. Roshandel et al. [18] have proposed an optimization task for linear PMSM which is based on a reduction in thrust ripple. Design optimization for maximum torque and efficiency of a line-start PMSM is performed using Response Surface Methodology and Finite Element Method [19]. Cogging torque minimization of surface-mounted PMSM is presented using Hybrid Magnet Shapes [20]. Design of outer-rotor PMSM for in-wheel electric drive train is carried out using Particle Swarm Optimization [21]. Optimal design of an interior PMSM is discussed by using a new Surrogate Assisted Multi-Objective Optimization [22]. Design optimization of a linear permanent magnet synchronous motor for extra low force pulsations is presented in Ref. [23]. PMSM with low torque ripple is designed [24] and PMSM with sinusoidal back EMF is designed by modifying its magnet shape [25]. In ref [26], different performance aspects of line-start PMSMs are discussed. Pole shape of PMSM is optimized by Reduced Basis Technique [27]. Control of PMSM drive is done with Neural Network [28]. High-efficiency PMSM is designed [29] and spoke-type PMSM is optimized combined design of experiments and differential evolution algorithms [30]. Optimization of PMSMs are performed and discussed by different evolutionary algorithms and different objective functions and optimization variables [31-35].

Aim of this paper is to optimally design a five-phase PMSM with surface-mounted magnet with the ratings of an engine propeller of an unmanned vehicle. For this purpose, Bees Algorithm (BA) is applied which is a novel optimization algorithm. In this Algorithm, the natural foraging behavior of honey bees is employed to find the optimal solution. Design optimization is performed with two types of objective functions which are combination of permanent magnets volume, torque and efficiency of the motor. It will be shown that, both types of optimization would reduce permanent magnets volume and in Type I, torque will be increased but efficiency will be decreased while in Type II efficiency will be increased but torque will be decreased. In next section, description of the PMSM is presented briefly.

In section 3, a brief description about Bees algorithm is given and optimization of the PMSM is discussed in section 4. After that in section 5, Finite Element Method (FEM) simulation is utilized to confirm the validity of the obtained results. Finally paper is concluded in section 6.

2 PMSM Description

Fig. 1 shows a schematic view of a surface-mounted PMSM. As shown, Permanent Magnets (PMs) are placed on the surface of the rotor. In this condition, motor is non-salient (cylindrical rotor) and it has some good characteristics over other types of permanent magnets. In these cases, there is just one reactance. The inductive reactance of the armature of a non-salient-pole (cylindrical rotor) synchronous machine with the magnetic saturation included is

$$X_a = 20\mu_0 f \frac{(N_{ph} k_w)^2 \tau_p L}{\pi P g'} \quad (1)$$

where μ_0 is the magnetic permeability of free space, τ_p is pole pitch, L is the axial length of the stator core [1-3].

Total copper loss is

$$P_{cu} = 5R_s (I_s)^2 \quad (2)$$

where R_s and I_s are resistance and current of every phase, respectively. Core loss can be calculated as follow

$$P_c = k_h f B_m^2 + k_e f^2 B_m^2 \quad (3)$$

where k_h and k_e are hysteresis and eddy constants. B_m is maximum flux density and f is frequency. Mechanical loss (Windage and friction loss) and stray loss are considered between 0.5 to 3 percent and 0.5 to 1 percent of the output power, respectively [3, 4]. Therefore, total loss is deduced as:

$$P_{Loss} = P_{cu} + P_c + P_{mech} + P_{stray} \quad (4)$$

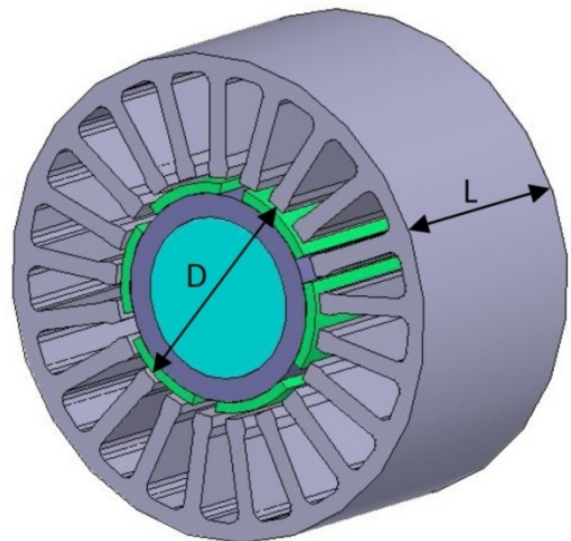


Fig. 1 Typical surface-mounted PMSM.

Now, efficiency is determined through the following equation:

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \quad (5)$$

Magnet volume is defined as follow

$$V_M = \alpha_i \left(\pi \left(\frac{D}{2} - g \right)^2 - \pi \left(\frac{D}{2} - g - l_m \right)^2 \right) L \quad (6)$$

where α_i is pole arc to pole pitch ratio and D is stator inner diameter (or air gap diameter). Finally, electromagnetic torque is calculated as follow [5].

$$T = \pi B_{av} L \left(\frac{D}{2} \right)^2 ac \quad (7)$$

in which B_{av} is specific magnetic loading and ac is specific electric loading of the motor. ac is the number of ampere-turns of armature in unit length of armature in air gap [4]. Detailed view of motor and parameters are given in Fig. 2. Besides, Fig. 3 illustrates five-phase winding configuration of the motor. Appendix A gives parameters and dimensions of a sample PMSM which is designed traditionally as a criterion for comparison to the optimized motor.

3 Bees Algorithm

Bees Algorithm is an optimization algorithm inspired by the natural foraging behavior of honey bees to find the optimal solution. Fig. 4 shows the flowchart of the pseudo code for the algorithm in its simplest form.

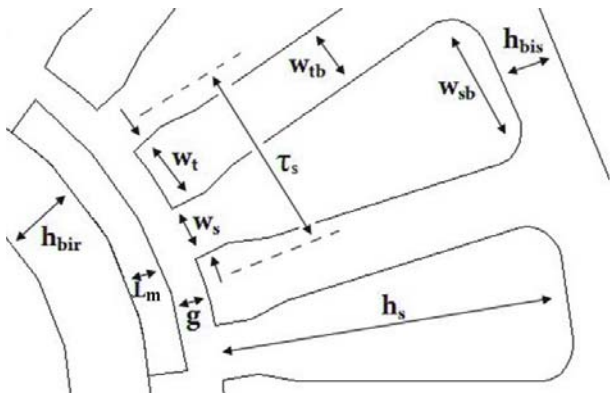


Fig. 2 Dimensions and parameters of the motor

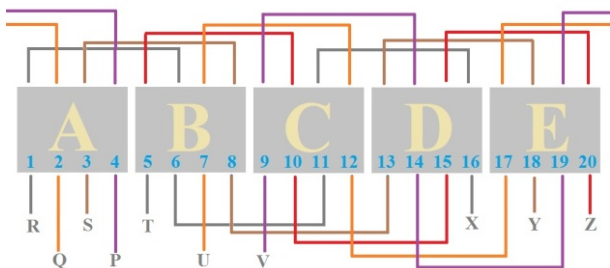


Fig. 3 Five-phase winding configuration.

Begin

- (1) Initialize the solution population.
- (2) Evaluate the fitness of the population.
- (3) While (stopping criterion is not met)//Forming new population.
- (4) Select sites for neighborhood search.
- (5) Recruit bees for selected sites (more bees for the best e sites) and evaluate fitnesses.
- (6) Select the fittest bee from each site.
- (7) Assign remaining bees to search randomly and evaluate their fitnesses.

End While

End

Fig. 4 Flowchart of the Pseudo code for optimization.

The algorithm requires a number of parameters to be set, namely: number of scout bees (n), number of sites selected out of n visited sites (m), number of best sites out of m selected sites (e), number of bees recruited for best e sites (nep), number of bees recruited for the other ($m-e$) selected sites (nsp), initial size of patches (ngh) which includes site and its neighborhood and stopping criterion. The algorithm starts with the n scout bees being placed randomly in the search space. The fitnesses of the sites visited by the scout bees are evaluated in step 2.

In step 4, bees that have the highest fitnesses are chosen as “selected bees” and sites visited by them are chosen for neighborhood search. Then, in steps 5 and 6, the algorithm conducts searches in the neighborhood of the selected sites, assigning more bees to search near to the best e sites. The bees can be chosen directly according to the fitnesses associated with the sites they are visiting.

Alternatively, the fitness values are used to determine the probability of the bees being selected. Searches in the neighborhood of the best e sites which represent more promising solutions are made more detailed by recruiting more bees to follow them than the other selected bees. Together with scouting, this differential recruitment is a key operation of the Bees Algorithm.

However, in step 6, for each patch only the bee with the highest fitness will be selected to form the next bee population. In nature, there is no such a restriction. This restriction is introduced here to reduce the number of points to be explored. In step 7, the remaining bees in the population are assigned randomly around the search space scouting for new potential solutions. These steps are repeated until the stopping criterion which in this case is the iteration is met. At the end of each iteration, the colony will have two parts to its new population representatives from each selected patch and other scout bees assigned to conduct random searches [36-39].

It should be noted that in this survey, population size is considered 100, iteration 500 and elite number 40.

4 Design Optimization

It is of interest that we have a motor with least volume and cost while the motor has to fulfill operational characteristics. When the motor has least permanent magnets volume (while magnets providing enough flux density), cost of manufacturing will be decreased. Besides, motor should have higher efficiency and torque. This causes the motor to operate in the optimal point.

In this paper, two types of objective functions are considered. Objective functions are combination of volume of the permanent magnets, torque and efficiency of the motor.

4.1 Type I

Objective function of this part is defined as follow

$$F = \frac{V_m(D, L, l_m, \alpha_i)}{T(D, L)} \quad (8)$$

which has to be minimized. In fact, this means minimizing PMs volume while maximizing torque, simultaneously. By doing this, the total objective function is optimized (minimized). In this survey, design variables are: L, D, l_m and α_i . These four variables are selected because of the objective function definition and the requirements of the application. Maximum and minimum ranges of design variables are listed in Table 1. Among these four variables, D and L vary in discrete ways. l_m and α_i are continuous variables.

After running optimization algorithm, optimum parameters are obtained. Fig. 5 shows objective function versus iteration. As shown in this figure, objective function converges and reaches to its optimal value i.e. 1.978 after 279 iterations.

The optimum values of the design variables are listed in Table 2.

Table 1 Minimum and maximum ranges of design variables.

Variable	Min	Max	Step
D (mm)	60	100	1
L (mm)	50	90	1
l_m (mm)	0.4	1	-
α_i	0.65	0.9	-

Table 2 Optimal values of design variables for Type I.

Dimension/Parameter	Value
D (mm)	73
L (mm)	61
l_m (mm)	0.6
α_i	0.78

Table 3 Specifications of typical and optimized motor for Type I.

	V_m (cm ³)	T (Nm)	η (%)
Typical motor	7.08	3.12	88.74
Optimized motor	6.33	3.37	88.57

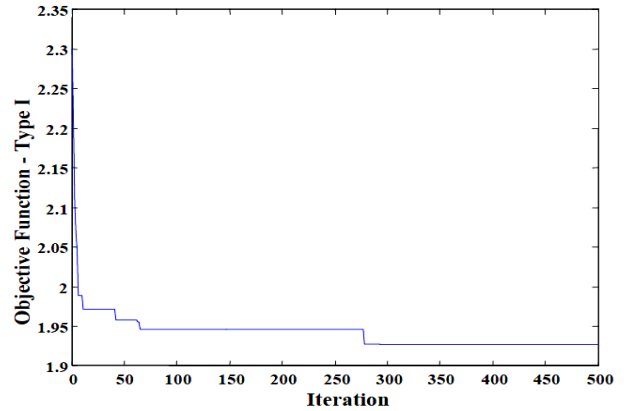


Fig. 5 Objective function versus iteration for Type I.

Comparing these results with the specifications of the typical motor (presented in the Appendix A) shows that the design optimization results in magnets with decreased height but pole arc to pole pitch ratio slightly increased. Moreover, D has increased and L decreased.

Table 3 compares magnets volume, torque and efficiency of the two designs. It can be seen that the optimization reduces the magnets volume by 10.59% and increases the torque by 8.01%. Besides, it is shown that efficiency slightly decreased. However, this reduction in efficiency is not too important and it doesn't affect the operational performance of motor.

4.2 Type II

Since in the previous definition of objective function, efficiency was decreased, in this part objective function is defined as follow

$$F = \frac{V_m(D, L, l_m, \alpha_i)}{\eta(D, L)} \quad (9)$$

Again, this function means minimizing magnets volume while maximizing efficiency, simultaneously. The total objective function has to be minimized.

After running optimization algorithm, optimum parameters are obtained. Fig. 6 shows objective function versus iterations.

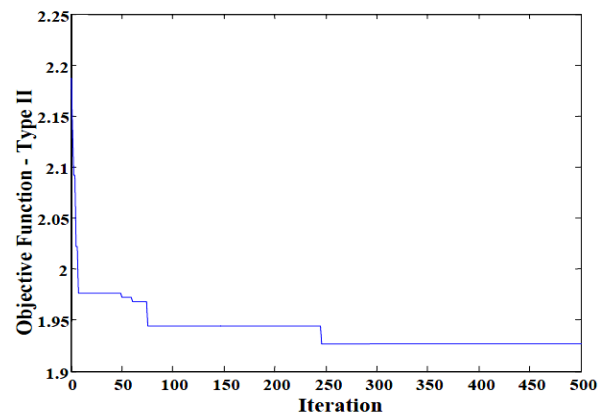


Fig. 6 Objective function versus iteration for Type II.

As shown, objective function converges and reaches to its optimal value i.e. 1.9263 after 246 iterations. The optimum values of the design variables are listed in Table 4. Again, the direction of variables variation is the same i.e. D and α_i are increased while L and l_m are decreased. However, there is a slight difference between the variables in Type I and Type II. Table 5 compares magnets volume, torque and efficiency of the two designs. As Type I, it is clear that the optimization reduces the PM volume by 20.6% but efficiency is increased just 0.4%. Moreover, it is shown that torque has decreased. In this case, reduction rate of magnets volume has almost doubled, but on the other side, efficiency has not increased too much.

Generally speaking, this optimization provides considerable advantages for the optimized motor over the typical one in terms of initial cost, volume and performance, because in both cases (Type I and II) permanent magnets volume was decreased and this reduction means reduction in cost of motor. Considering all aspects of this research, it is concluded that optimization should be performed based on the application of the motor. In other words, no optimization method can increase torque and efficiency in the same time and one of them has to be sacrificed.

4.3 Comparison with Other Algorithms

Now, Bees algorithm is compared with two well-known evolutionary algorithms i.e. Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithm in order to show the superiority of the proposed method. Table 6 and 7 illustrate the comparison of BA with GA and PSO for Type I and Type II, respectively. It is noted that, the weighting factors for the three algorithms are chosen identical to have a fair comparison. As shown in the Tables 6 and 7, BA has higher capability and fulfills the requirements of the optimization, because the fitnesses obtained by BA have much differences with respect to the typical design compared with GA and PSO. Besides, BA converges quicker and the reliability of the results is higher comparing to the GA and PSO algorithms.

Table 4 Optimal values of design variables for Type II.

Dimension/Parameter	Value
D (mm)	68
L (mm)	62
l_m (mm)	0.55
α_i	0.8

Table 5 Specifications of typical and optimized motor for Type II.

	V_m (cm ³)	T (Nm)	η (%)
Typical motor	7.08	3.12	88.74
Optimized motor	5.62	2.97	89.12

Table 6 Comparison of BA with GA and PSO for Type I.

	V_m (cm ³)	T (Nm)	η (%)	Abs. Difference (%)		
				V_m	T	η
Typical Design	7.08	3.12	88.74			
BA Design	6.33	3.37	88.57	10.59	8.01	0.019
GA Design	6.37	3.32	88.68	10.02	6.41	0.006
PSO Design	6.42	3.35	88.61	9.32	7.37	0.014

Table 7 Comparison of BA with GA and PSO for Type II.

	V_m (cm ³)	T (Nm)	η (%)	Abs. Difference (%)		
				V_m	T	η
Typical Design	7.08	3.12	88.74			
BA Design	5.62	2.97	89.12	20.62	4.8	0.42
GA Design	5.86	2.99	89.06	17.23	4.1	0.36
PSO Design	5.95	3.03	89.04	15.96	2.8	0.33

Table 8 BH curve of material.

B [T]	H [A/m]	B [T]	H [A/m]
0.0	0	1.6915	7957.7
0.2282	159.2	1.81075	15915.5
0.82215	318.3	1.92575	31831
1.0551	477.5	1.98375	47746.5
1.18355	636.6	2.0275	63662
1.2645	795.8	2.06175	79577.5
1.4251	1591.5	2.176	159155
1.5202	3183.1	2.38075	318310
1.59915	4774.6	2.48084	397887
1.65435	6366.2	3.48179	1193660

5 Finite Element Method Validation

The design optimization in this paper is totally based on analytical models of motor presented. Therefore, the accuracy of the electrical and magnetic models validates the design optimization. In this section, finite element method (FEM) is used for validation. Maxwell software which is based on FEM is one of the most important and efficient tools for this purpose.

We give the software the dimensions obtained by optimization (Type I). A 2D FEM simulation is carried out and the numerical and graphical results are obtained. The effect of magnetic saturation was included in the FEM software by using B-H curves of the materials. B-H curves of this material of the stator and rotor steel are presented in Table 8. Fig. 7 shows finite element mesh of the motor. Fig. 8 shows flux lines diagram. Fig. 9 shows voltage and current of one phase of motor. As shown in Fig. 9, RMS value of phase voltage and phase

current is close to the rated values of motor. Also, moving torque of motor is shown in Fig. 10. This torque value has minimum deviation with the one obtained by analytical design.

Table 9 presents a comparison between results of analytical optimization and finite element method.

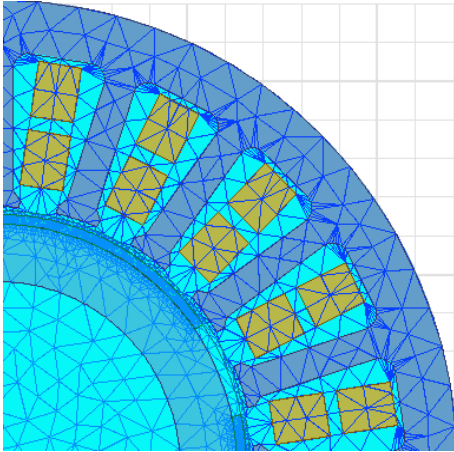


Fig. 7 Finite element mesh.

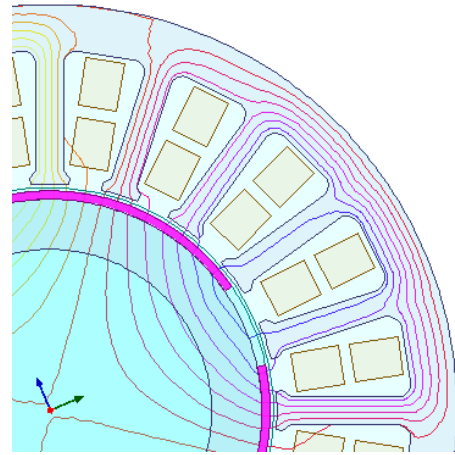


Fig. 8 Flux lines diagram.

Table 9 Comparison of analytical optimization and FEM results.

Results	Analytical	FEM	Error (%)
X_a (Ω)	25.53	23.257	8.9
T (Nm)	3.37	3.186	5.4
Efficiency (%)	88.57	90.68	1.8

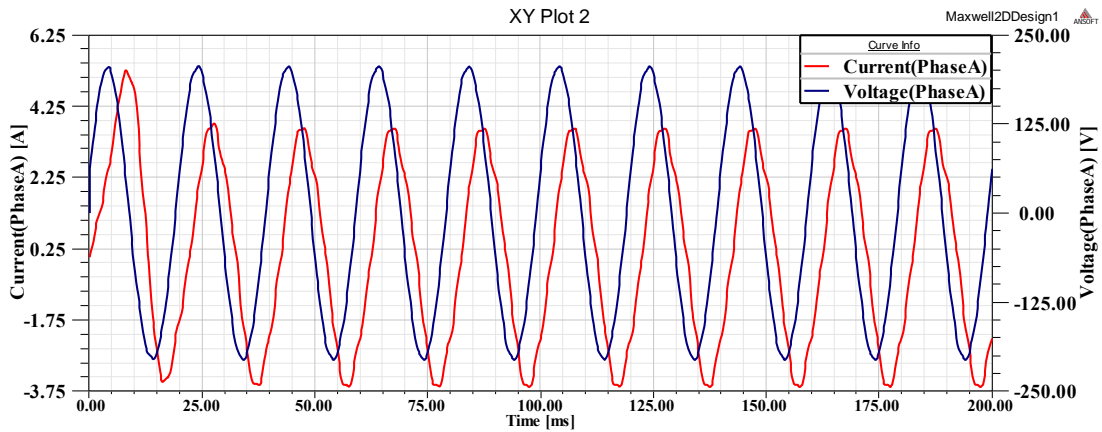


Fig. 9 Voltage and current of one phase.

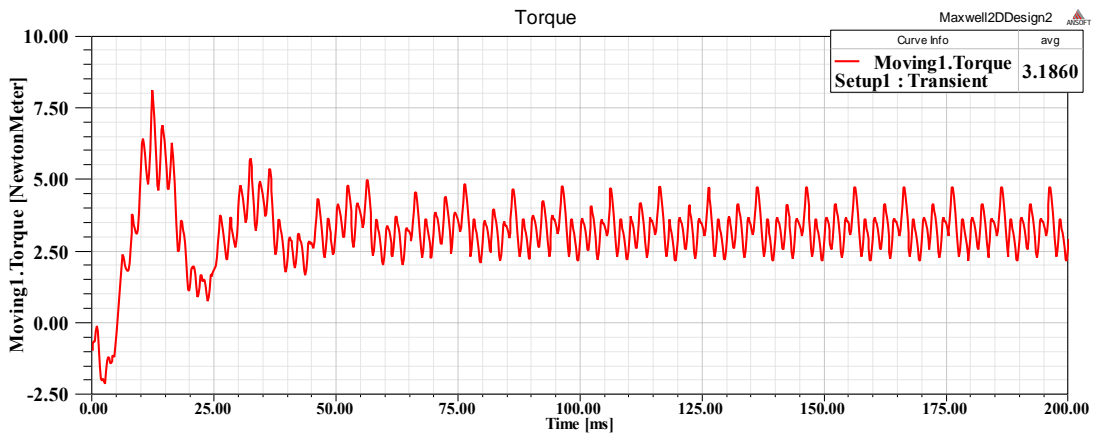


Fig. 10 Moving torque of motor.

6 Conclusion

This paper presented design optimization of five-phase surface-mounted permanent magnet synchronous motors. Design optimization is performed in search for proper dimensions of motor and its magnets. Two types of objective functions were introduced. In both of them, permanent magnets volume was major part and in both cases (Type I and II) permanent magnets volume was decreased. On the other hand, in Type I torque has increased but efficiency decreased while in Type II efficiency has increased but torque decreased. It is concluded that optimization has to be carried out based on the requirements of application. In other words, objective function is defined for a specific aim. For example, when a motor with least permanent magnets volume is required, the permanent magnets volume has to be included in the objective function and the optimization would concentrate on this objective. Besides, in practice, optimization would not improve all the performance characteristics of the motor (such as efficiency or torque) at the same time. In fact, there should be a trade-off between the output performances of the motor. After that, BA was compared with GA and PSO and superiority of BA was proved based on the results of fitnesses. Finally, finite element method confirmed the analytical optimal design with minimum error which proves the efficiency and accuracy of the design optimization.

Appendix

Table A1 Typical motor specifications used as a basis for comparison.

Parameter	Description	Value
P_{out}	Output Power	550 W
V_n	Rated Voltage	220 V
P	Number of poles	4
n_s	Rated Speed	1500 rpm
I_s	Phase Current	1.4 A
F	Drive Frequency	50 Hz
D	Stator Inner Diameter	67.5 mm
L	Motor Axial Length	66.1 mm
D_{out}	Stator Outer Diameter	121 mm
h_{bi}	Stator yoke height	8.8 mm
h_s	Slot height	18 mm
l_m	Permanent Magnet height	0.7 mm
α_i	Pole arc to pole pitch ratio	0.75
G	Air Gap Length	0.9 mm
B_{av}	Specific magnetic loading	0.6 T
A_c	Specific electric loading	22000 A/m
B_r	Remanent flux density	1.2 T
B_s	Saturation flux density	1.5 T
τ_p	Pole Pitch	52.9 mm
K_w	Winding factor	0.95
S	Slot number	20
N_{ph}	Stator Turns per Phase	343
Z_{slot}	Number of Conductors per Slot	171
R_s	Stator Resistance per Phase	4.5 Ω

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